

The absorption spectrum around $\nu = 1$: evidence for a small size Skyrmion

J. G. Groshaus,* V. Umansky, H. Shtrikman, Y. Levinson, and I. Bar-Joseph

Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot, Israel.

We measure the absorption spectrum of a two-dimensional electron system (2DES) in a GaAs quantum well in the presence of a perpendicular magnetic field. We focus on the absorption spectrum into the lowest Landau Level around $\nu = 1$. We find that the spectrum consists of bound electron-hole complexes, trion and exciton like. We show that their oscillator strength is a powerful probe of the 2DES spatial correlations. We find that near $\nu = 1$ the 2DES ground state consists of Skyrmions of small size (a few magnetic lengths).

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Electron-electron interactions are known to play an important role in determining the ground state of a two-dimensional electron system (2DES) around $\nu = 1$. They favor a ferromagnetic order at this filling factor even in the absence of a Zeeman spin gap. Furthermore, it was suggested that if this spin gap is sufficiently small, the ground state around $\nu = 1$ consists of charged spin-textures excitations known as Skyrmions [1, 2]: neighboring electrons tend to align their spin in parallel to minimize the exchange energy, creating a smooth texture of the spin field, in which many electrons participate. The projection of the spin along the magnetic field direction, S_z , varies gradually from the center of the texture towards the edges, with the total integrated charge being $-|e|$ for $\nu > 1$ (Skyrmion) and $+|e|$ (anti-Skyrmion) for $\nu < 1$. It has been realized that as the spin gap increases such a large size structure becomes very costly in energy. Less electrons find it energetically favorable to flip their spin, and the Skyrmion size shrinks. Theoretical estimates for GaAs ($g = -0.44$) set the Skyrmion size at $B = 8$ T to be about two magnetic lengths only [2]. The experimental evidence for the Skyrmion theory comes primarily from NMR measurements [3], tilted magnetic field transport experiments [4], and optical absorption spectroscopy [5]. In these measurements the spin polarization $\langle S_z \rangle$ of the 2DES was determined, and was shown to fall abruptly at both sides of $\nu = 1$, as predicted by the theory.

In this paper we wish to use optical absorption spectroscopy to study the 2DES ground state in this regime. A major problem in interpreting optical measurements of 2DES is how to account for the strong Coulomb interaction between the valence hole and the surrounding electrons. Recent experimental and theoretical works show that the optical spectrum in the fractional quantum Hall regime should be understood in terms of bound electron-hole complexes, e.g. neutral and charged (trions) excitons [6, 7, 8, 9]. In this paper we find clear evidence for the formation of these bound electron-hole complexes around $\nu = 1$ and show that they can be a powerful probe for the ground state of the 2DES. A measurement of their oscillator strength (OS) and energy dependence on ν al-

lows us to estimate the Skyrmion size, and we show that only a few electrons significantly contribute to it.

The experiments were done at a temperature of 4.2 K, and a magnetic field of up to 9 T applied along the growth axis of the wafer. The light source was a tunable Ti-sapphire ring laser, and the sample was illuminated with power densities I_L lower than 1 mW/cm² through a thick plastic optical fiber and a circular polarizer. Reversing the polarization of the light was accomplished by reversing the direction of the magnetic field B . To obtain the absorption spectrum we measured the photo-current (PC) flowing between the 2DES and a back gate. We have previously demonstrated this technique in obtaining the absorption spectrum of a 2DES at $B = 0$ using a front gate[10]. We find that the PC at laser energies below the fundamental gap is negligible, resulting in background free spectral measurements. This also gives us confidence that the measured PC spectrum indeed reflects the quantum well absorption spectrum. This was further verified by conducting complementary photoluminescence excitation measurements, where similar qualitative behavior of the peak positions and line shape were observed. Several samples with the same general structure were investigated, all consisting of a single 20 nm GaAs/Al_{0.3}Ga_{0.7}As modulation-doped quantum well grown on top of a 0.5 μ m Al_{0.3}Ga_{0.7}As barrier layer, separating it from the back gate layer. The wafers were processed to a mesa structure with selective ohmic contacts to the 2DES and to the back-gate. Applying a voltage between the 2DES and the back gate we could tune the electron density n_e continuously.

Figure 1(a) presents a compilation of PC measurements at constant n_e as B is varied between -9 T and $+9$ T. The magnitude of the PC is color-coded, with dark-red color indicating strong absorption. The characteristic Landau levels fan is well resolved even at low fields. The lowest energy line for both signs of B corresponds to an absorption process from the heavy-hole (hh) band into the lowest electron Landau level (LLL). It has a sharp onset at $B = \pm 3.6$ T, corresponding to $\nu = 2$: below this magnetic field the LLL is full, so that no absorption is possible. This allows us to obtain n_e at each gate volt-

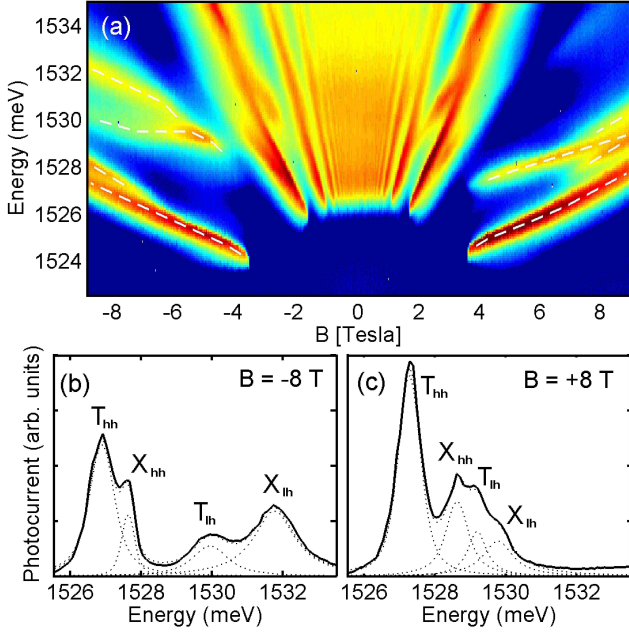


FIG. 1: (a) (color) Photocurrent spectra for $n_e = 1.7 \times 10^{11} \text{ cm}^{-2}$ and $I_L = 0.3 \text{ mW/cm}^2$. The dashed lines are guide to the eye. (b, c) Spectra at both polarizations (solid line) for $\nu < 1$, where both the singlet trion T and the exciton X are present for heavy and light holes. The dotted lines are the fitted functions.

age. A few meV above this line and parallel to it there is an additional line in both directions of B . It corresponds to the creation of a light-hole (lh) - electron pair. We note that the hh and lh lines (marked by dashed lines) at a given direction of B probe different electronic Zeeman levels: for $B < 0$ a σ^+ photon tuned to the hh transition creates a valence hole with $J_z = 3/2$ and an electron with $S_z = -1/2$. When tuned to the lh transition it creates a valence hole with $J_z = 1/2$ and an electron with $S_z = 1/2$. In other words, for $B < 0$ the hh transition probes the electron lower Zeeman state $|\uparrow\rangle$, while the lh probes the upper Zeeman state $|\downarrow\rangle$. Similarly, for $B > 0$ the hh and lh transitions create an electron in the $|\downarrow\rangle$ and $|\uparrow\rangle$ states, respectively.

Examining Fig. 1(a) carefully we note that at high magnetic fields, below $\nu = 1$, a new absorption line appears above each of the lh and hh LLL lines. These new lines are particularly visible at the negative fields ($B < 0$) spectra, where the large hh-lh splitting allows us to easily resolve them. Figures 1(b) and 1(c) show the spectrum at $B = -8$ T and $+8$ T, respectively, above the branching field. It is evident that the spectrum consists of four peaks at each light polarization.

To identify the nature of the peaks we followed their evolution with density. We found that as the electron density is decreased, for both hh and lh transitions the lower energy peak evolves continuously into the singlet

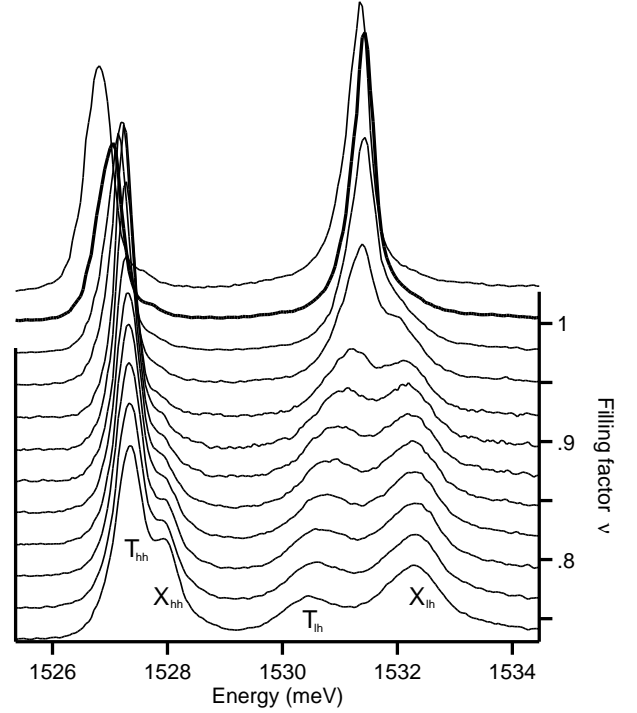


FIG. 2: Evolution of the spectra of both heavy and light hole excitons X and trions T as a function of the density at $B = -9$ T and $I_L = 3 \mu\text{W/cm}^2$. The $\nu = 1$ spectrum is emphasized by a thick line. It is seen that both X lines appear abruptly below $\nu = 1$.

trion T while the high energy peak develops into the neutral exciton X [11]. These bound complexes were intensively studied in dilute 2DES during the last decade, and their identification is well established [10, 12]. We note that such continuous evolution of the X and T peaks from the dilute limit to higher electron densities was observed in both photoluminescence and absorption measurements in the fractional quantum Hall regime [6, 9]. We therefore conclude that the lines that are observed around $\nu = 1$ are due to the formation of bound complexes of a similar nature.

Figure 2 shows the evolution of spectrum as n_e is decreased below $\nu = 1$ [13]. It is clearly seen that at $\nu = 1$ new satellite peaks, X_{hh} and X_{lh} , abruptly appear above the two lower energy peaks, T_{hh} and T_{lh} , and gain OS as the density is further reduced. We repeated these measurements in several samples at various magnetic fields and electron densities and confirmed that this is indeed a filling-factor dependent phenomena that occurs at $\nu = 1$ for both hh and lh transitions and both light polarizations.

To quantitatively determine the behavior of the X and T peaks as a function of ν we have fitted each spectrum, such as those depicted in Figs. 1(b) and 1(c), to a sum of four Voigt functions. This allowed us to obtain the pa-

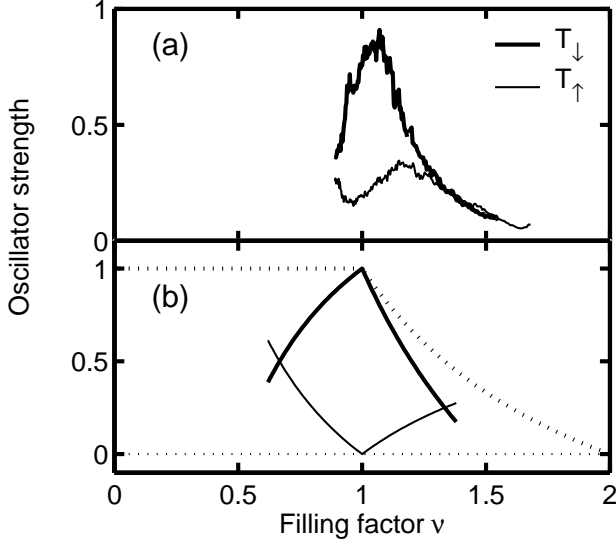


FIG. 3: (a) The oscillator strength of T_{lh} for both polarizations at constant $n_e = 1.8 \times 10^{11} \text{ cm}^{-2}$. (b) The calculated values of $|M_{T,\downarrow}|^2$ and $|M_{T,\uparrow}|^2$ with $u_m = \delta_{m,0}$ as B is scanned. The dotted line corresponds to free electron picture ($u_m = 0$). The values of $|M|^2$ are normalized by dividing by $N_\phi|_{\nu=1}$.

rameters of each peak: the OS, the peak energy and the line width. Figure 3(a) shows the OS of T_{lh} at both polarizations as B is varied at constant n_e . We can see that at $\nu = 1$ there is a pronounced maximum in the absorption into the electron $|\downarrow\rangle$ state and a corresponding minimum for $|\uparrow\rangle$. Away from $\nu = 1$ the absorption in both polarizations becomes nearly equal, indicating a depolarization of the 2DES. We observe a similar behavior by varying n_e at a constant magnetic field. This dependence of the OS on ν is similar to that reported by Aifer *et al.* [5]. We note, however, that that work does not correctly identify the X - T splitting and describes the absorption as a single particle process, neglecting the electron-hole interaction. It is evident from our data that a proper interpretation of the experiment should account for the creation of bound e-h complexes. In the following we present such a formulation and show that it yields a new insight into the nature of the ground state of the 2DES.

The wave function of a magneto-exciton in an empty well ($n_e = 0$) [7] can be written in the LLL approximation, which neglects higher Landau levels mixing, as $|X_{\downarrow}\rangle = \sum_{m=0}^{N_\phi-1} h_{m,\uparrow}^\dagger c_{m,\downarrow}^\dagger |0\rangle$, where the $c_{m,\downarrow}^\dagger$ ($h_{m,\uparrow}^\dagger$) operator creates an electron (valence hole) in the corresponding spin state of the orbital $\phi_m(r)$ with angular momentum m , and N_ϕ is the LLL degeneracy (an analogous expression can be written for $|X_{\uparrow}\rangle$). On the other hand, it is well known that upon increasing n_e the dominant absorption process becomes the creation of a singlet trion, a bound state of two electrons in a singlet state and a valence hole. Thus, when dealing with a 2DES near $\nu = 1$

we make the following conjecture: two bound complexes, X and T , may be created in an absorption process, depending on the energy of the photon. The X complex is created only in orbitals ϕ_m which are *empty in both spin states*, while T is created only in orbitals in which *one electron is already present*. This conjecture preserves the nature of the bound complexes as in the dilute limit, and in particular - the singlet character of T [14]. The final states upon absorption into $|\downarrow\rangle$ can thus be written (up to normalization) as

$$|X_{\downarrow}\rangle = \sum_{m=0}^{N_\phi-1} h_{m,\uparrow}^\dagger c_{m,\downarrow}^\dagger c_{m,\uparrow}^\dagger c_{m,\uparrow}^\dagger |\psi\rangle, \quad (1)$$

$$|T_{\downarrow}\rangle = \sum_{m=0}^{N_\phi-1} h_{m,\uparrow}^\dagger c_{m,\downarrow}^\dagger c_{m,\uparrow}^\dagger c_{m,\uparrow} |\psi\rangle,$$

where $|\psi\rangle$ is the state of the 2DES prior to absorption, and analogous expressions can be written for the opposite polarization. We shall show below that the observed behavior of the OS cannot be explained assuming the initial state $|\psi\rangle$ to be of non-interacting electrons. Therefore, we employ a model of interacting electrons, assuming that the initial state close to $\nu = 1$ and low enough temperature is a *dilute gas of Skyrmions and anti-Skyrmions* and the OS is the sum of their contributions. Following Ref. [2] we write the initial state at zero temperature at $\nu = 1$ as $|\psi_0\rangle = \prod_{m=0}^{N_\phi-1} c_{m,\uparrow} |0\rangle$, and the wave function of a single Skyrmion or anti-Skyrmion as

$$|\psi_{-}\rangle = \prod_{m=0}^{N_\phi-1} (u_m c_{m,\downarrow}^\dagger + v_m c_{m+1,\uparrow}^\dagger) |0\rangle, \quad (2)$$

$$|\psi_{+}\rangle = \prod_{m=0}^{N_\phi-1} (-u_m c_{m+1,\downarrow}^\dagger + v_m c_{m,\uparrow}^\dagger) c_{0,\downarrow}^\dagger |0\rangle,$$

with $|u_m|^2 + |v_m|^2 = 1$ and $u_m \rightarrow 0$ as $m \rightarrow \infty$. The free electron model is obtained by setting $u_m = 0$ and $v_m = 1$ for all m .

The OS is proportional to the absolute value squared of the matrix elements $M = \langle i | \sum_{m,s} h_{m,s}^\dagger c_{m,s}^\dagger | f \rangle$, and it is straightforward to show that it can be written explicitly for the four lines as

$$|M_{X_{\downarrow,\uparrow}}|^2 = N_a (|v_0|^2 + \sum |u_{m-1}|^2 |v_m|^2) + N_s \left(\sum |v_{m-1}|^2 |u_m|^2 \right), \quad (3)$$

$$|M_{T_{\downarrow}}|^2 = N_\phi - (N_s + N_a) \left(1 + \sum |u_{m-1}|^2 |v_m|^2 + |u_m|^2 \right),$$

$$|M_{T_{\uparrow}}|^2 = (N_s + N_a) \left(|u_0|^2 + \sum |u_{m-1}|^2 |u_m|^2 \right),$$

where all sums are over m from $m = 1$ to $m = N_\phi - 1$, and N_s and N_a are the number of Skyrmions and anti-

Skyrmions, respectively. Equation (3) allows us to calculate the OS dependence on ν at zero temperature, where $N_s = N_\phi(\nu - 1)$, $N_a = 0$ for $\nu > 1$ and $N_s = 0$, $N_a = N_\phi(1 - \nu)$ for $\nu < 1$. It is easy to see that the free electron model does not yield the observed behavior of the trion OS. This model predicts $|M_{T_\uparrow}|^2 = 0$ for any ν , in a clear contradiction with the experimental result, which shows a strong T_\uparrow -absorption away from $\nu = 1$. Furthermore, it gives a constant T_\uparrow -absorption for $\nu < 1$ when changing ν at constant n_e (B -scan), while the experiment shows a sharp drop [Fig. 3(a)]. In the Skyrmionic model, on the other hand, the sharp maximum in the T_\uparrow -absorption and the minimum in T_\uparrow are readily explained assuming that at least $u_0 \neq 0$. According to the model, as ν is tuned away from 1, the Skyrmion effects reduce the T_\uparrow -absorption and transfer the corresponding OS to the T_\uparrow -absorption.

The behavior of the X -absorption, which vanishes for $\nu > 1$, sets an upper bound for the Skyrmion size. It follows from Eq. (3) that the X -absorption is strongly asymmetric with respect to $\nu = 1$. In order to explain the observed vanishing of the OS for $\nu > 1$ one has to assume that $u_m \approx 0$ for $m \geq 1$. This implies that only electrons at $m = 0$ and 1 contribute significantly to the Skyrmion. This result follows from the assumption that the exciton is formed in orbitals where both spin states are empty, implicitly allowing the nearest neighboring orbitals to be occupied [Eq. (1)]. If one requires that these orbitals are also unoccupied, the upper bound on the Skyrmion size will be higher: in order for $|M_X|^2$ to vanish for $\nu > 1$ it will suffice to assume that all $u_m \approx 0$ for $m \geq m_0$, where m_0 is the number of neighbors considered. Thus, the actual number of electrons involved in a Skyrmion may be larger than two, but of this order of magnitude. The conclusion is that only a few electron orbitals participate in the Skyrmion texture.

Figure 3(b) depicts the calculated OS of T_\downarrow and T_\uparrow at zero temperature for both the free electron model and for a small Skyrmion ($u_{m \geq 1} = 0$). It is seen that the calculation reproduces qualitatively the experimental data. The asymmetry around $\nu = 1$ is due to the change in N_ϕ as B is scanned. The effect of a finite temperature is particularly important close to $\nu = 1$, where thermal spin excitations are dominant. As a result, in the experiment the respective peak and dip in the OS of T_\downarrow and T_\uparrow are smoothed.

Remarkably, the symmetry of the T -absorption around $\nu = 1$ is observed in the peak energy and width as well. Figure 4(a) shows the energies of the $X_{lh,\downarrow}$ and $T_{lh,\downarrow}$ as a function of ν . It is seen that the T_{lh} energy is maximal at $\nu = 1$ and drops symmetrically at both sides. Similarly, we show in Fig. 4(b) the full width at half maximum of the T_{lh} peak in the same polarization. It is clearly seen that the width is minimal at $\nu = 1$ and rises symmetrically at both sides. These observations are another manifestation of the electron-hole symmetry of the

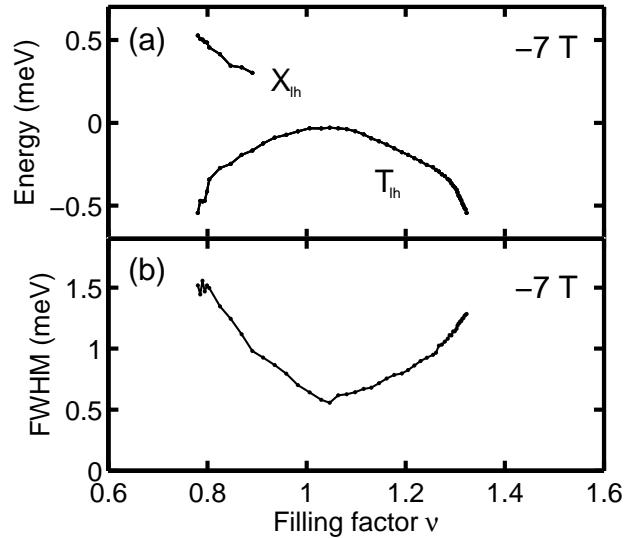


FIG. 4: (a) The energy of the $X_{lh,\downarrow}$ and $T_{lh,\downarrow}$ as a function of n_e at constant B . The scale was shifted by 1530.3 meV for clarity. (b) FWHM of the $T_{lh,\downarrow}$. Notice the symmetry of the energy and width around $\nu = 1$.

Skyrmionic ground state [2]. A quantitative treatment of this behavior is, however, beyond the scope of this paper.

Finally, we wish to note that $X - T$ splitting is also observed at higher Landau levels [see Fig. 1(a) around ± 2.5 T]. This splitting occurs around $\nu = 3$, and another one is observed around $\nu = 5$. This might provide an opportunity to explore the existence of Skyrmions at high filling factors as well [15].

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* Electronic address: j.groshaus@weizmann.ac.il

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